CONFIDENTIAL

AD 351 091 L

CLASSIFICATION CHANGED
TO: CONFIDENTIAL
FROM: SECRET
AUTHORITY:
DOD 5200.1-R Nov 73

CONFIDENTIAL

SECRET

AD 351091L

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION, ALEXANDRIA, VIRGINIA

SECRET

SECRET

NRL Memorandum Report 1541

Copy No. 9 of 75 copies

BALLISTIC EVALUATIONS OF COMPOSITE ARMOR

(UNCLASSIFIED TITLE)

W. J. Ferguson, E. R. Seibert,
and C. J. Skowronek

MECHANICS DIVISION

351091

June 1964

This document contains proprietary information and may not be reproduced or released without prior permission of the originating office.

U. S. NAVAL RESEARCH LABORATORY
Washington, D.C.

SECRET
Downgraded at 12 year intervals;
Not automatically declassified.

01244

CONTENTS

ABSTRACT

Ballistic evaluations of beryllium, beryllium-Doron, alumina-Doron and alumina-beryllium-Doron were conducted with caliber 0.22-inch and/or caliber 0.30-inch missiles at normal incidence. The areal densities of the targets extended from 1.5 to 10 lbs/ft^2. The beryllium-Doron composites exhibited excellent fragment armor characteristics while the alumina-Doron composites provided outstanding protection against a single hit type impact by an AP-M2 projectile. The three-phase composite exhibits an improved ballistic limit over either of the two-phase composites at the same areal density against caliber 0.30-inch projectiles.

Variations in target composition, structure and support had little if any effect upon the ballistic limit velocities determined on the alumina-Doron composites except that a minimum thickness of about 0.25 inches of alumina is required to cause sufficient core blunting and breakup of the AP-M2 projectile to result in a good armor.

PROBLEM STATUS

This is an interim report. Work on this problem is continuing.

AUTHORIZATION

NRL Problem No. F04-15
Project No. RRMA-02-090/6521/R007-01-01

INTRODUCTION

This work was initiated as a result of previous experimental data obtained at NRL and reported in Ref. (1). It was found that composite targets made from beryllium and Doron were superior to other armor materials (within the same areal density range) when subjected to attack by steel spheres. About the time the present work was started, encouraging ballistic data, obtained on alumina-Doron composites tested with caliber 0.30-inch armor piercing projectiles, became available from industrial sources (the information was provided orally or on single data sheets, therefore a reference is not available). The alumina-Doron composites impacted with caliber 0.30-inch AP projectiles were reported to be superior to any other armor material for the target areal density tested (approx. 9.0 lbs/ft^2). The areal density ranges of the two types of composites did not overlap. The early data on both of these composites indicated a large synergistic effect. The beryllium and alumina (Al_2O_3) used in these composites have high Young's moduli and relatively low densities, although the two materials differ by almost a factor of two in specific gravity. Both materials exhibit ballistic brittleness; however the extent of fracturing and target breakup is much greater for alumina targets than for beryllium targets.

Knowledge was not available with regard to many factors which might influence missile penetration resistance of these two specific composite targets. Among these factors were: the effect of the mass percentage of each component used in a composite target of given areal density; the effect of the method by which the target components were joined; effect of target size, including the effect of area of the square plate facing material (ceramic or beryllium); effect of target supporting frame and other factors which might influence the penetration resistance. It was not known whether or not the composites would be superior to other armor materials for target areal densities which had not been tested.

Since there is no penetration theory which will allow one to predict accurately the ballistic limit velocity of homogeneous targets made of different materials when subjected to attack by a wide range of missile masses and shapes over a wide range of target areal densities and missile velocities, it was decided that a purely theoretical study was unlikely to offer a satisfactory explanation for the results which had been observed or provide information necessary to produce even better composite armor materials or structures.

The approach to obtaining an understanding of the mechanisms involved was planned as an experimental program involving predominately ballistic tests of composite targets, supplemented with other experimental data, to determine the effects of Young's modulus, sonic velocity, and other physical and mechanical properties upon the transfer of energy across the boundary between the components of composites. Those factors to be determined from ballistic tests of composite targets included: (a) the minimum thickness of alumina required for alumina-Doron targets which would result in both blunting of the point of the caliber 0.30-inch AP-M2 projectile and breakup of the main part of the core to the rear of the ogive; (b) the effect of the type of adhesive used to bond beryllium or alumina to Doron when tested with fragment simulating projectiles and AP projectiles; (c) the effect of percentage of Al_2O_3 from which the ceramic is made when tested as an alumina-Doron composite with caliber 0.30-inch AP projectiles; (d) the performance of beryllium-Doron composites when attacked by caliber 0.30-inch AP and ball projectiles; (e) ballistic data to allow comparison of the beryllium-Doron and alumina-Doron composite targets with homogeneous armor materials at more than one areal density. The areal density figures presented for the composite materials represent the sum of the areal densities of the principal components and do not include an allowance for the bonding materials. The double surface adhesive tape and the Proseal 890 resin used as bonding agents had areal densities of 0.025 lb/ft^2 and approximately 0.1 lb/ft^2, respectively, for the thicknesses used. Careful observation of both the targets and projectiles after testing was included in an effort to deduce from phenomenological aspects the mechanisms involved. Other experiments planned included studies of the strain distribution between composite materials subjected to impact over a large range of impact velocities. Through the use of a thin layer of photoelastic material between two different materials it was proposed to determine the degree and distribution of strain resulting from impacting the surface of the specimens by counting the number of fringes induced in the photoelastic material and the area or distance over which they were distributed. To accomplish this requires that the specimens be made from narrow strips, which reduces the problem to one in two dimensions and results in specimens which are quite different with respect to component and total rigidity from specimens of semi-infinite dimensions in the plane of the specimen surface. Nevertheless it was believed that the type of observations considered possible would yield quantitative data to indicate the extent and distribution of loading of the rear component of a composite target resulting from changes in the physical properties of the facing material.

STRESS DISTRIBUTION UNDER IMPACT LOADING

In an effort to understand the mechanisms involved in the synergistic effect (increased performance of a composite over that afforded by each of its components acting alone) found in some composite targets, a series of experiments was performed to determine the stress distribution transmitted by the back surface of the initial component to the adjacent component. Materials for the test specimens were selected so that modulus and density varied over a fairly wide range, allowing the examination of the effect of sonic velocity in the material ($\sqrt{E/\rho}$) on the transmitted stress distribution. Tests were conducted at impacting velocities of approximately 5 ft/sec and low ballistic velocities which more closely approximated true ballistic impact.

A dark field polariscope and photographic techniques were used to determine the fringe pattern in a thin strip of photoelastic material, placed between the components, as a function of time. This was accomplished by taking photographs of successive impacts at predetermined intervals after impact for the quasi-static tests and by using a high speed framing camera and multiple flash units for the ballistic tests. Materials included in the tests were steel, aluminum, titanium, beryllium, 6 Mg/Li-Al and Doron as the facing component and steel, aluminum and Doron as the backing component. Test specimens were in the shape of bars having approximately equal areal densities 6 in. long and 0.2 in. wide. Since areal density appears to be a significant factor in penetration resistance, constant areal density was selected for the tests.

The results of the quasi-static tests indicate that there is good agreement between the observed stress distribution and the stress distribution calculated using an equivalent static load and the Winkler formula for a beam on an elastic foundation which will not support a tensile load. In general, the stress developed at the point behind the point of impact is lower, delayed in time, and persists for a longer time when the back component is of aluminum or Doron than when the back component is steel.

Instrumentation and control difficulties in the ballistic tests prevent any quantitative conclusion from being drawn from these tests at present, and the ballistic tests have been suspended pending development of improved experimental technique. A new approach to the determination of the stress distribution using pressure-sensitive resistance transducers, is being considered to circumvent the problems encountered in the photoelastic techniques.

BALLISTIC TESTS, RESULTS AND DISCUSSION

The test equipment and facilities used were essentially the same as those used in the earlier ballistic investigations of beryllium and Doron composites as reported in Ref. (1). A new sealed target chamber was used for part of the shots on composites utilizing beryllium. This differed from the earlier chamber in that it provided more versatility in target mounting and included facilities for target assembly, cleaning and storage. The safety precautions described in the earlier work were also utilized during this investigation.

The velocity of the projectile was determined by using the time for the projectile to pass between two grids separated by a measured distance. The velocity grid base lengths utilized were either one or two feet measured to the nearest 1/64 of an inch. The counter chronograph, which was started by the breaking of the first grid and stopped by that of the second, read directly to the fifth decimal place with the sixth being read to the nearest sixteenth. The overall error of the velocity measuring system is less than one quarter of one percent.

A. Targets tested with steel spheres and fragment simulating missiles

Beryllium, beryllium-Doron, and alumina-Doron targets were tested with caliber 0.22-inch steel spheres, T-37 fragment simulators, and/or yawed dart fragment simulators.

The available physical and mechanical properties provided by the manufacturer of the materials purchased by NRL for this work are given in Tables 1 and 2. Additional targets were obtained in an exchange of materials between the Chemical Warfare Laboratories, Edgewood, Maryland and NRL. These items are described in footnotes to Table 5.

The beryllium plates as indicated in Table 2 were produced by hot pressing or rolling. The elongation, yield strength and ultimate strength of the rolled material are higher than those of the hot pressed material. For rolled material, the property values given are generally higher for the 0.2-inch thick plates than for 0.4-inch thick plates. For a given thickness, even when the plates are rolled from the same heat, there is considerable variation in properties of plates rolled at different times (for example the two sets of values given in Table 2 for 0.2-inch thick plate made from Heat No. 455-D).

The mechanical properties of rolled material, particularly the elongation, vary with reference to the direction of rolling. The elongation of the hot pressed material at equal thicknesses (either 0.20" or 0.40") is quite different from heat to heat.

The effect of elongation, etc., upon the performance of beryllium as an armor material alone or in combination with other materials as composite armor was not known. At the time of purchase of the beryllium it was expected that the primary difference in physical properties would be between the hot pressed and the rolled plates with the properties of each group being more nearly uniform than indicated in Table 2. The material was purchased using minimum values of the yield strength and elongation established upon the basis of values which suppliers indicated could be obtained.

Because of variations in properties from one group of beryllium plates to another, a question arose about the validity of using a ballistic limit determined from all groups of plates as representative of beryllium in general. As a consequence, an effort was made to perform ballistic tests in such a manner as to determine what effect the variations in properties had upon the ballistic limit velocity for plates tested alone and as a beryllium-Doron composite. To have done this conclusively for all properties of initial concern (ultimate tensile strength, yield strength, and elongation); for two or three types of missiles; for several plate thicknesses; and for both rolled and hot pressed plate, would have required more material than was available. The beryllium plates used for the various limit velocities are indicated by plate number. The mechanical properties of these plates are presented in Table 2.

All of the ballistic data given for tests of beryllium and beryllium-Doron targets tested with steel spheres and 22 caliber fragment simulators are for projectile through-the-plate ballistic limits. This type of ballistic limit velocity, V_L, is defined as the average of two velocities, one of which is the highest observed velocity for which the missile did not pass completely through the target, and the other is the lowest velocity at which complete penetration of the target was accomplished. The half difference between these two velocities is appended to the limit velocity by the ± sign. For those instances where complete penetration is accomplished at a velocity lower than another for which the missile does not pass completely through the target, the half difference is appended by the ∓ sign.

Another type of ballistic limit designated as the protection ballistic limit velocity, V_p, involves the use of an 0.020-inch thick bare aluminum sheet placed approximately six inches to the rear of and parallel to the target surface. The protection ballistic limit velocity, V_p, is then assigned in the same manner as V_L except that a complete penetration is defined as one in which the missile or any part of the missile and/or target material causes an opening in the aluminum witness plate which permits light to pass through it. When less damage occurs the result is defined as an incomplete penetration irrespective of whether or not the projectile passes through the target. The protection ballistic limit, V_p, may be equal to, greater than, or less than the missile through-the-plate limit velocity, V_L. For targets which do not cause missile breakup or lose target material in the form of petals, spalls or plugs, V_p and V_L are very nearly equal, with V_p being higher by the amount necessary to cause a hole in the 0.020-inch thick aluminum witness plate.

V_L type limits obtained with 0.22-inch diameter spheres are given in Table 3. As indicated in the remarks on Tables 3 and 4, the effects of elongation and tensile strength on the ballistic limit of beryllium plates alone are ambiguous. For composite targets of beryllium-Doron there is a preference for the use of the more ductile rolled plate over the hot pressed material. Typical photographs of targets after impact with steel spheres are shown in Figs. 1 and 2.

The results of tests of beryllium alone and of beryllium-Doron targets with T-37 fragment simulating missiles are given in Table 4. A ballistic limit was not determined for the 0.2-inch thick beryllium because it was less than 926 ft/sec. This was sufficient to show that the beryllium at this areal density and with this test missile was inferior to other armor materials.

It was not possible to obtain a V_L for the 0.4-inch thick beryllium alone. The plate remained intact up to 2095 ft/sec with the depth of penetration estimated to be less than one-fourth of the plate thickness. At higher velocities the plate spalled and/or cracked. For this type target it is difficult to obtain meaningful ballistic data based upon missile through-the-target ballistic limits. Results obtained with the composite targets of beryllium and Doron show that the use of the rolled plate is preferable to hot pressed plate. This is in agreement with the conclusion from tests with the steel spheres on the same type of targets. Although missile through-the-target ballistic limits were obtained on these composite targets, the results of the tests were such that V_L would not differ appreciably from V_P.

Ballistic limits were determined with 22 caliber spheres and T-37 fragment simulators for both the beryllium-Doron and the alumina-Doron targets. All data are based upon protection ballistic limits except for the beryllium-Doron targets tested with the T-37 fragment simulator. The data obtained with the fragment simulator are given in Fig. 3 along with data for other excellent quality fragment armor materials. As noted above, V_P for these targets would be slightly higher than V_L. Both composite armors show a greater rate of increase of ballistic limit as a function of target areal density than the other armor materials. Comparisons of ballistic limits of other armor materials with the alumina-Doron composites when tested with caliber 0.22-inch spheres and yawed dart fragment simulators are given in Table 5. The alumina-Doron targets are inferior to available fragment armor materials for the test missiles used (spheres, T-37 and yawed dart fragment simulators) for target areal densities below about 2.5 lbs/ft^2. For the composite targets the variations used in methods of target mounting, methods of attaching beryllium or alumina to Doron backing, or changes in area of Doron backing did not significantly affect the ballistic limit velocity.

The beryllium-Doron targets are superior to other fragment armor materials for the target areal densities tested. The data shown for beryllium-Doron targets in Fig. 3 are for targets where rolled beryllium plates were used and represent the most favorable comparison with other materials. Extrapolation of the limited data for beryllium-Doron targets indicates that this type target will not offer a substantial increase in ballistic limit velocity, if any, over other good fragment armor materials for areal densities below about 1.5 lbs/ft^2.

B. Alumina-Doron composite targets tested with caliber 0.30-inch Ball-M2 and AP-M2 projectiles

Alumina-Doron composites of approximately 9.0 lbs/ft^2 were purchased from Goodyear Aircraft Company. The Doron was ten by ten inches in size and the alumina facings, which were either five by five inches or five and one-half by five and one-half inches were centered on the Doron. The alumina was obtained from Coors Porcelain Corp. in two grades. The available material properties as reported by material supplier are given in Table 1. NRL purchased two grades of alumina tile from International Pipe and Ceramics Corp. These are designated as GMcB grades 352 and 395 in Table 1. All GMcB tiles were five by five inches. Prior to obtaining either the Goodyear composite armor or the NRL purchased components for making composites, preliminary tests were made on available alumina tiles which had been used in connection with a thermal study of ceramics. This material was in the form of six-inch diameter disks with 5/8-inch diameter holes drilled in the center of each disk. The disks were cut in half for use in the preliminary tests described below. These disks are identified in Table 1, as Norton Grade A402. The Doron used at NRL in the fabrication of all targets of either alumina-Doron or beryllium-Doron was produced from No. 143 fiberglass fabric bonded with a polyester resin. Specification Mil-I-17368(MC) was followed in so far as practical in production of the Doron. The specification does not cover the areal density of Doron used; however fabric style, resin type, percentages, etc., conformed with the specification. Doron used was purchased from two manufacturers.

There has been considerable oral and written conjecture that the mechanisms involved in defeating the armor piercing projectile with alumina-Doron armor include breakup of the tungsten carbide core of the projectile and turning action of the core as an entity. Breakup of the projectile and/or blunting of the ogive (nose) of the projectile core is without doubt an important factor. This principle was used in the development of face hardened aircraft armor (FHAA) and was described in the literature over two decades ago, Ref. (2), "Superior resistance to bullets by hard bullet-proof plates compared with homogeneous plates cannot occur except by ability to break the projectiles." During the development of FHAA, efforts were made to obtain hard faces on homogeneous steel plate by nitriding and other techniques, Ref. (3 and 4). Such hard faces were not adequate to cause sufficient blunting or breakup of the AP tungsten carbide core to result in a good quality FHAA except for relatively thin plates for which these techniques permitted hardening to a substantial portion of the plate thickness (approx. 30 percent). It was also found that: (1) there exists an optimum hardness of the facing material; (2) the optimum thickness of the hard facing is dependent upon the test missile, test conditions (for example obliquity) and ratio of target thickness to missile diameter, Ref. (3). It was demonstrated that the presence of a thin ($\approx$ 0.050-inch thick) soft surface layer resulted in a drastic lowering of the ballistic limit velocity as compared to plates without the thin soft layer. This change in ballistic limit velocity was associated with missile breakage, Ref. (3). The hardness of the back portion of the target was found to have an important effect on penetration resistance. FHAA armor made by adhering a hard face of about 600 BHN to a softer backing provided an excellent armor for protection from caliber 30 AP-M2 projectiles. It was evident from prior work on hard face armor that the minimum thickness of hard facing required to provide good results would be at least that thickness which would severely blunt the ogival point of the projectile core and/or cause the core to break up.

It has been observed in the testing of metallic armor materials with caliber 0.30-inch AP-M2 projectiles that small amounts of yaw and/or obliquity may have a large effect upon the penetration resistance of the armor, Ref. (5 and 6). The possibility that small amounts of yaw would cause a significant effect upon the penetration of the hard faced ceramic armor was considered likely. No effort has been made to determine whether or not such an effect does occur; rather, effort was concentrated upon elimination of yaw. At short distances from the muzzle of the gun barrel the yaw is usually less than at a distance of several feet. A test facility was set up with the distance from the barrel muzzle to the target of 29 inches. Several barrels were used to fire in this facility. Two barrels for which there was no apparent yaw over a wide velocity range as evidenced by firing into metallic targets and observing the projectile in the target were selected for use in testing.

Additional firings were made over trajectory distances of 12 feet for which no yaw was apparent in a vast majority of cases. All ballistic tests with caliber 0.30-inch Ball-M2 and AP-M2 projectiles have been made with the trajectory normal to the target face and at distances between 29 inches and 10.75 feet.

Our first experiments with alumina-Doron composites were conducted to determine the minimum thickness of alumina which, when backed with Doron, would cause blunting of the projectile core and core breakup. GMcB grade 395 alumina tiles in thicknesses of one-tenth and two-tenths of an inch were backed with three-eighths-inch thick Doron plates 12 x 12 inches. These targets were supported by 1 x 1 inch steel posts on two sides and by a one-inch thick steel plate along a third edge and were held to the steel posts with "C" clamps. It was found that for 0.10-inch thick alumina, blunting of the AP projectile core did not occur to any appreciable extent over a velocity range from a few hundred feet per second up to velocities sufficient to cuase target penetration. The extent of core damage was greater for the 0.2-inch thick alumina than for 0.10-inch thick alumina. Tests using 0.25-inch thick Norton alumina grade A402 backed with Doron showed that considerable damage to the ogival point of the projectile core occurred at and above 794 ft/sec. The point of the projectile penetrated to a depth of approximately one-fourth the thickness of the alumina facing at 794 ft/sec. The extent of core damage increased with velocity and core breakup occurred at velocities below that necessary to penetrate the entire target. Photographs of recovered projectile cores are provided in Fig. 4. These experiments demonstrated that an alumina thickness of less than 0.20 inch would not cause sufficient AP core damage to result in a good armor. One may question whether or not it is legitimate to draw conclusions from the above experiments without knowledge as to the effect of using alumina of different sizes, grades, and from different sources. These factors are covered in the conclusions, at the end of this section.

In chronological sequence the next testing was of the two groups of targets purchased from Goodyear Aircraft Corp. The protection ballistic limit velocity was determined with AP-M2 projectiles for the two grades of alumina. Comparison of the results (See Items 1 and 2 of Table 3) led to a tentative conclusion that targets made from 99 percent alumina were superior to those made from 94 percent alumina. Although there was a small difference in the areal density of the two types of targets, it was not anticipated that this difference in areal density would result in the approximately ten percent difference in ballistic limit velocity observed. In tests of these targets the alumina was generally shattered over an area approximately two inches in diameter. Some delamination occurred to the edges of the Doron, and an occasional target had shear type breaks to the edge of the Doron. Tests with caliber 0.30-inch Ball-M2 projectiles of the Goodyear produced targets using AD-94 alumina resulted in delamination of the Doron to a greater extent and some bulging of the Doron at the back surface. Typical targets are shown in the upper left corners of Figs. 5 and 6 for impacts with AP-M2 and Ball-M2 projectiles. From previous experiments on the effect of Doron target area and attendant delamination (i.e. tests where the target area was varied from small targets where the conditions were such that delamination between layers of glass fabric occurred to all edges of the targets up to areas where no delamination occurred to the target edges), it was believed that the 10 x 10 Doron plates were sufficiently large to result in the same ballistic limit velocity as would be obtained with an infinite area plate. In continuation of the experiments using NRL made samples, it was decided to reduce the area of the Doron in order to conserve material. The size was reduced to 8 7/8 x 8 7/8 inches.

The targets to be made at NRL were to have alumina tile of different thickness and sizes from those made by Goodyear. The Doron to be used was made by different manufacturers. It was considered desirable to demonstrate whether or not these differences, combined with any differences in the Goodyear and NRL techniques of bonding the components, had an influence upon the penetration resistance of the targets. To do this the alumina was removed from seven of the Goodyear samples made with 94 percent alumina. The alumina was bonded to NRL procured Doron using Proseal 890 resin which is the same resin used by Goodyear. A resin thickness of 0.020 inches was troweled onto the Doron, and the alumina placed upon this and allowed to cure at room temperature. For two of the seven tiles it was necessary to put approximately 0.030 inches of resin on the Doron since unevenness of the tile surfaces exceeded 0.020 inches. The thickness of resin between the alumina and Doron was not uniform for targets made from any of the tiles removed from the Goodyear specimens because of unevenness of the tile surfaces. It is assumed that this is also true in general for all of the targets purchased from Goodyear. The NRL purchased Doron to which these Goodyear tiles were bonded was of equal areal density to the Doron used by Goodyear. Although a protection ballistic limit velocity was not obtained with these targets, the testing performed demonstrated that there was no large difference between the Goodyear and NRL produced targets when tested with the AP projectiles (see Items 1 and 3 of Table 6). It is believed that the performance of targets produced at NRL does not differ from those made by Goodyear because of differences in materials or in the technique of attaching the alumina to the Doron with Proseal 890.

A series of specimens were made from the two types of GMcB alumina bonded to 8 7/8 x 8 7/8 inch Doron. The alumina was attached by one of three methods: (a) Proseal 890 using 0.020 inch thickness which after seating of the alumina and curing resulted in an approximately 0.015 inch thickness of resin; (b) Araldite 502 epoxy resin which was selected because of its high static and dynamic Young's modulus; and (c) by using a 0.005-inch thick double surface adhesive tape (Scotch brand pressure sensitive tape No. 406). The alumina tiles for these experiments had ground surfaces which were specified flat to within 0.001 inch and were in fact so smooth that two tiles could be picked up together from a table top by lifting the upper tile. The Doron was also flat so that the thickness of resin between each tile and the Doron was uniform. The resin thickness was uniform for the targets using Proseal 890 but varied from 0.004 to 0.012 inch from sample to sample for the epoxy bonded targets. The epoxy resin thickness variation from sample to sample was due to our inexperience in working with this resin and could easily be avoided; however, it is believed that this variation was of no consequence in the behavior of the target in the ballistic tests.

After testing this series of specimens with caliber 0.30-inch AP-M2 projectiles, it was concluded that neither the percent Al_2O_3 (95% or 99%) nor the method of bonding the tiles to the Doron had a significant effect upon the protection ballistic limit velocity (Data are given in Table 7 and a typical target is shown in the upper right corner of Fig. 5).

Tests with caliber 0.030-inch Ball-M2 projectiles resulted in extensive bulging and delamination of the 8 7/8 x 8 7/8 inch Doron (see upper right corner of Fig. 6). It was believed that this could have a significant effect upon the ballistic limit velocity. In previous ballistic tests of Doron alone with fragment simulating missiles, significant lowering of the ballistic limit velocity had resulted in going from target areas where bulging and extensive delamination occurred to larger specimens where delamination to the target periphery did not occur. Since the targets were already prepared, it was decided to provide restraint along all edges. This was done by taking two one-half inch thick pieces of 2024T4 aluminum alloy 12 x 12 inches and cutting out central areas 7 1/8 x 7 1/8 inches. The targets were centered between the two pieces of aluminum and the two pieces of aluminum held together by eight 1/4 inch screws which were tightened evenly. A 7/8th inch width of the Doron was held between the aluminum frames along each edge. It was hoped that this would prevent the extensive bulging and delamination to the Doron periphery. The bulging was decreased, but some delamination and breakage to the Doron periphery still occurred. For the Goodyear 99% alumina, and 10 x 10 inch Doron targets impacted at velocities below that necessary to cause complete penetration of the targets with caliber 0.30-inch Ball-M2 projectiles, there was reverse buckling; that is, the rear surface of the Doron after impact was closer to the gun barrel than before impact. This is shown at the lower left, Fig. 6. In similar tests with caliber 0.30-inch AP-M2 projectiles no reverse buckling occurred. It was apparent that the phenomenological aspects of these clamped targets were different from those likely to be obtained in tests of targets with infinite Doron plates, and that it should not be assumed that ballistic limit velocities would be the same for the caliber 0.30-inch Ball-M2 projectile.

Tests were made using various types of targets clamped in frames with caliber 0.30-inch Ball-M2 and AP-M2 projectiles. The ballistic limit velocities for tests with both AP-M2 and Ball-M2 projectiles were found to be the same as obtained for the same type of targets unclamped (see Items 1 and 2 of Table 6; Items 1 and 2, Table 7; and Item 1 of Table 8). With clamping the 8 7/8 x 8 7/8 inch Doron delaminated to the edges when impacted with Ball-M2 projectiles; therefore it was decided to make targets with 12 x 12 inch Doron backing.

Several additional tests were performed which involved changes in target assembly, target mounting, and test facilities. The data are presented in Tables 6, 7, 8, and 9 with detailed explanations in the Table footnotes. Typical target appearances are given in Figs. 5 and 6. No effort will be made to guide the reader through the laborious details of individual tests and the reasons for the various changes made. Attention is called to Figs. 7 and 8 which give data and photographs of targets impacted off center and of others which had a piece of 0.030-inch thick alclad aluminum taped to the alumina facing.

The protection ballistic limit velocities for all of the alumina-Doron targets tested with AP-M2 projectiles are plotted as a function of areal density in Fig. 10. These data include variations in method of bonding alumina to Doron, Doron area dimensions, percent Al_2O_3 of the ceramic, source of the tiles, and method of holding the targets. They were obtained using three different test facilities. Typical examples of AP-M2 projectile breakup are shown in Fig. 9.

Although the data points in Fig. 10 are not identified in the legend, one may identify each point by referring to the Tables. Most of the data fit a single smooth curve. The targets for data points which are more than ±50 ft/sec off the curve (vertical displacement) were not sufficiently different in construction from other individual target types for which the data fall on the curve to allow a plausible explanation for these deviations. The curve shown in Fig. 10 is redrawn in Fig. 12 which also includes a segment of a curve given in Ref. 6 which has been adopted by the U. S. Army Materials Research Agency as a standard against which comparisons are made of experimental material. The U. S. Army Materials Command has established a policy of classifying ballistic data "Secret" when the ballistic limit velocity of the test material is at least twice that of an equal areal density target of the standard for comparison. From Fig. 12 it is seen that the alumina-Doron targets tested with caliber 0.30-inch AP-M2 projectiles have ballistic limits twice that of the standard (a Specification rolled steel armor) for areal densities of about

9.25 lbs/ft^3 and above. Data above 9.25 lbs/ft^3 would be classified "Secret" whereas that below 9.25 lbs/ft^3 if presented alone would be classified "Confidential".

Figure 11 provides data obtained upon various alumina-Doron targets tested with caliber 0.30-inch Ball-M2 projectiles. The four data points obtained upon targets using 99% Al_2O_3 fall on a smooth curve. The data obtained upon two targets using 94 or 95% Al_2O_3 fall slightly below the curve. It is suggested that there may be an improvement in penetration resistance with use of 99% over 95% Al_2O_3, although the difference is small.

CONCLUSIONS FOR SECTION B

With respect to the protection ballistic limit velocity, tests with both AP-M2 and Ball M-2 projectiles show that:

*1. Methods used for bonding of alumina to Doron had no effect. See Table 7.

2. Method of support for the several methods used had no effect.

3. The Al_2O_3 content (94 to 99.3 percent) of the ceramic had little effect.

4. Source of alumina used had little if any effect.

5. The percent by weight of alumina (between about 58 and 67 percent) had little if any effect provided the alumina thickness was greater than the minimum required to cause extensive damage to AP-M2 projectile cores.

For AP-M2 projectiles only:

1. Size of Doron backing used had no effect.

*2. Impacting the alumina off center did not result in appreciable lowering of the limit velocity. This conclusion is based upon the data for only two shots (data presented in Fig. 7). No off-center impacts were made with Ball-M2 projectiles.

---

*These conclusions either contradict or do not support conclusions reported orally by others.

*3. Bonding an 0.030-inch thick 2024-T3 aluminum sheet to the alumina did not lower the limit velocity. The limited tests were insufficient to determine whether or not the limit velocity would increase sufficiently to compensate for the added weight. This factor is discussed in the section on future plans. No such tests were made with Ball-M2 projectiles. See Fig. 8.

4. A minimum thickness of alumina of about 0.25 inch was required to accomplish adequate blunting and core breakup to result in a good armor. See Fig. 4.

C. Alumina-Beryllium-Doron Composites

The result of the tests on alumina-Doron targets and beryllium-Doron targets showed the former to offer excellent resistance to penetration by the armor piercing projectiles and the latter to be excellent when attacked by fragment simulating projectiles. The only beryllium-Doron target tested with AP-M2 projectiles was found to be inferior to the alumina-Doron targets.

It was postulated that the use of a composite of three components could be made which might be superior to either the alumina-Doron or beryllium-Doron against both AP projectiles and fragment simulating projectiles. The ballistic data, observations of target behavior and postulated mechanisms involved in the penetration led to the alumina-beryllium-Doron composites. Evidence from some tests with caliber 0.30-inch AP-M2 projectiles suggests that, in addition to the destruction of the nose of the projectile core by the hard alumina facing, reflected stress waves are causing fractures of the core. Examples have been observed where the core was fractured with plane surfaces perpendicular to the long axis of the projectile. Even if this occurred regularly, it probably would not be observed often if the fracturing took place in the early stages of penetration since the core parts would have considerable momentum and additional breakup would occur when they impacted the target. It was observed in tests of beryllium with steel spheres and T-37 fragment simulators that large, deep spalls of beryllium occurred. It is believed that a large amount of projectile energy is required either to push the projectile through this beryllium spall or to push the spall through the Doron back-up.

*These conclusions either contradict or do not support conclusions reported orally by others.

The target compositions used for the three-phase composites are given in Table 10. From the tests of the two component composites it was expected that for equal areal density, these three-layer composites would be superior to the alumina-Doron composites when attacked by fragment simulating projectiles. The critical test of performance of the three-layer targets was considered to be attack by AP projectiles. The results of these tests are given in Fig. 13. Tests performed with caliber 0.30-in. AP-M2 projectiles on targets having areal densities of 6.1 and 9.40 lbs/ft^2 result in protection ballistic limit velocities which are 100-150 ft/sec higher than for equal areal density alumina-Doron targets. Figure 14 provides photographs of targets after impact at velocities below the ballistic limit velocity. The spall off the back of the beryllium for the impact velocity of 2670 ft/sec is over three inches in diameter. This spall is separated by an annular fracture about one and one-half inches in diameter as shown in the upper right of Fig. 14. This behavior is typical for the beryllium and was observed for beryllium and beryllium-Doron targets tested with steel spheres and fragment simulating missiles.

A three component target was tested with caliber 0.30-inch Ball-M2 projectiles at 6.22 lbs/ft^2. The result is plotted in Fig. 13.

No tests have been made of the alumina-beryllium-Doron targets with fragment simulating projectiles. No effort has been made to determine the proportion of the multiple component targets which should be made from each material. To do this through extensive ballistic testing of targets is considered prohibitive because of the cost of beryllium. The results of the ballistic tests of beryllium-Doron composites using caliber 0.22-inch missiles were influenced by the variability in the properties of the beryllium. The 0.4-inch thick beryllium used in the three-phase composites was hot pressed plate. Beryllium with properties appreciably greater than for the grade used has been made. It is estimated that the use of beryllium with the higher physical and mechanical properties as a replacement for the plate used in the three-phase targets may result in an increase in ballistic limit velocity of ten to twenty percent. Reference 8 shows that composites of boron carbide-Doron are superior to the three-phase targets tested to date based upon data obtained with caliber 0.30-inch AP-M2 projectiles.

CONCLUSIONS

Tests performed on alumina-Doron composite targets in the areal density range between about 1.25 and 4.5 lbs/ft^2 with caliber 0.22-inch spheres and 0.22-inch fragment simulating missiles and on targets with areal densities between about 6.0 and 9.5 lbs/ft^2 with caliber 0.30-inch AP-M2 and Ball-M2 projectiles show that the rate of increase in ballistic limit velocity as a function of areal density is greater in general than for other armor materials. Also, within the rather broad range of means used of bonding or holding the components together or methods of mounting targets there was no significant effect upon the ballistic limit. For the particular case of attack by Ball-M2 projectiles, the size of the Doron backing plate may be significant.

Against caliber 0.30-inch Ball-M2 and AP-M2 projectiles, alumina-Doron composite targets in the areal density range 6.0 to 11.0 lbs/ft^2 offer excellent protection against a single hit type impact. A minimum thickness of about 0.25 inches of alumina is required for two-phase alumina-Doron targets in order to accomplish sufficient core blunting and breakup of the AP-M2 projectile to result in a good armor.

Two-phase composite targets of rolled beryllium-Doron are superior to alumina-Doron when subjected to attack by fragment simulating projectiles and steel spheres within the range of target areal densities and attack conditions investigated. Also, composites using rolled beryllium were superior ballistically to those using the hot pressed material. It is expected that increased ductility and uniformity of the mechanical properties of rolled plates would result in improvement in the ballistic penetration resistance over the reported values. The two-phase composites of alumina-Doron are superior to other good fragment armor materials when tested with the T-37 fragment simulator using targets having areal densities above about 2.5 lbs/ft^2, and inferior at areal densities less than 2.5 lbs/ft^2. Tests of alumina-Doron at areal densities between 1.3 and 2.5 lbs/ft^2 with both 0.22-inch diameter spheres and the caliber 0.22-inch yawed dart fragment simulator show these tabgets to be inferior to other good armor. Extrapolation of data obtained on beryllium-Doron targets suggests that there will be little or possibly no improvement in penetration resistance of this type target over other good armor materials for targets having areal densities of 1.0 - 1.5 lbs/ft^2, the areal density range commonly used for personnel armored garments.

Observations of target and missile damage in tests of two-phase compesites of alumina-Doron and beryllium-Doron resulted in postulation of mechanisms involved in the penetration which led to the construction of three-phase composites. Limited tests have been made on only one type of three-phase composite. This target type provided slightly higher levels of protection from attack by caliber 0.30-inch AP-M2 and Ball-M2 projectiles than is afforded by equal areal density alumina-Doron targets. These projectiles are the only types used to test three-phase composites to date. As detailed in the text, these test conditions were those believed to be the most severe in determining the merits of using this composite; therefore the results obtained are considered significant.

These composites possess characteristics which may preclude their use as armor materials for many applications. Because of the extreme toxicity of beryllium the composites containing this metal may be unsuitable for use where personnel are likely to be exposed to dust or fragments formed during penetration by missiles. The damage to the alumina-Doron composites resulting from a single impact is sufficient, in most cases, to render the composite incapable of defeating a second impact in the surrounding area. Armor applications often involve the use of the material to provide a dual function, that of an armor and structural material. The composites in their present form do not compare favorably with homogenous metals for use as structural materials.

Acknowledgements

The authors wish to acknowledge the assistance of Messrs. D. P. McGogney and L. A. McKelleget whose diligent and effective efforts in the laboratory phase of this investigation have contributed significantly to the advancement of this project. Appreciation is also expressed to Messrs. F. R. Stonesifer and P. W. Mast for their contribution in the planning and execution of the phase of the project dealing with stress distribution under impact loading.

FUTURE PLANS

1. Tests of alumina-beryllium-Doron targets with caliber 0.30-inch and/or caliber 0.50-inch fragment simulators will be made in the areal density range of 6.0 - 10.0 lbs/ft^2, so that the penetration resistance of this composite can be compared with that of alumina-Doron and other two-phase composites.

2. Tests will be made of three- and four-phase composites for which the impact surface is a relatively thin sheet of high strength steel or titanium. Based upon observations of tests ith caliber 0.30-inch AP-M2 and Ball-M2 projectiles, it appears that such a facing could restrain displacement of the ceramic component, resulting in increased breakup and deformation of these projectiles. Restraint of lateral displacement (which would be provided for impacted tiles by the adjoining tiles in large plates of armor) may also increase projectile damage in defeating the ceramic portion of the target. If this scheme operates as envisioned it may permit a substantial reduction in the thickness of ceramic required to accomplish breakup of AP cores.

It is believed that the latter will be essential to obtain a substantial improvement in penetration resistance of equal areal density targets since prior experience does not indicate that the proposed thin metal facing will result in extensive damage to the AP projectile. The metal facing and lateral restraint of the ceramic may severely restrict the area of ceramic damaged thereby providing greater protection against multiple hits within a small area.

3. Tests are planned using two-phase composites in which the Al_2O_3 is replaced by silicon carbide. Since at least a portion of the mechanism of AP projectile defeat is by blunting of the projectile core, the harder material is expected to be more effective. Table 11 provides some handbook values of hardness and other properties of a variety of materials. It is believed that a high value of $\sqrt{E/\rho}$ is desirable for materials to be used as the primary facing component. If the results indicate a significant improvement over the use of Al_2O_3, silicon carbide may be used in n-phase composites.

Plans also included the use of boron carbides. This was eliminated because of recently reported work being performed by or under contract to Watertown Arsenal Laboratories, Ref. 8. The results reported in that reference show the harder carbide-Doron composite to be superior to other composites when tested with caliber 0.30-inch AP-M2 projectiles.

4. Tests will be made using Ball-M2 projectiles as test missiles on targets for which the rigidity of the backing material is increased moderately over that of Doron. Glass fabric laminates using epoxy resins and the 6 Mg/Li-6Al alloy developed under BuWeps sponsorship as an armor material will probably be included among the backing materials.

5. A technique has been proposed by NRL personnel which is believed, will permit the determination of stress at the interface of composite targets. The appearance of some of the composite targets and the permanent displacements which take place lead one to suspect that loading by the projectile of the target may be sustained for relatively long periods of time as compared to projectiles penetrating homogenous metallic targets (the latter has been measured and reported in Ref. 9). If this is true, then measurements of the magnitude, area over which applied, and the time duration of transmitted forces at the component faces would provide quantitative data for the selection of the materials and proportion of each to be used in the production of composite targets.

Preliminary trials will be limited to attempts to measure the magnitude and time duration of the interface stresses at one or two positions. If large differences in these factors are observed for different composites, the work should then be extended to include observations at several positions over the interface area. The sensing devices could not be reused and a large quantity of high-speed recording equipment will be needed in this phase of the work.

REFERENCES

1. Ferguson, W. J., Seibert, E. R., and Skowronek, C.J., "Ballistics Tests of Beryllium and Doron Arranged as a Composite," NRL Report 5939 (SECRET), 7 June 1963

2. Irwin, G. R., "Ninth Partial Report on Light Armor," NRL Report 1778, 4 Sept 1941

3. "Metallurgy of Face-Hardened Light Armor," NPG Report, 25 Sept 1944

4. Hodge, J. M., and Joyce, H.V., "A Study of Ballistic and Metallurgical Characteristics of Steel Aircraft Armor," Carnegie-Illinois Steel Corp. Report to NRL under Contract N-173-S-11392, June 25, 1948

5. Irwin, G. R., "The Effect of Yaw Upon Penetration; The Effect Upon Bullets of Penetrating Very Thin Duralumin Sheets; and the Use of Shielding Structures in the Form of Grating," NRL Report 1540, 19 June 1939

6. Irwin, G. R., and Webster, R. Alden, "Seventh Partial Report on Light Armor," NRL Report 1600, 21 March 1940

7. Hegge, E. N., and Medeiros, M. F., "Current Technology of Light Armor Materials for U. S. Army Aircraft," U. S. Army Materials Research Agency Report AMRA MS 63-03, 14 May 1963 (Confidiential)

8. U.S.A.M.R.A. Letter Report No. AA-56, 28 March 1964, Progress Report on Aircraft Armor Program, 1 July 1963 - 28 March 1964 (U), Secret

9. Masket, Albert V. H., "The Longitudinal Vibrations of a Projectile During Armor Penetration," NRL Report 2275, 13 April 1944

Table 1. Physical and Mechanical Properties of Aluminum Oxide (Alumina)

Manufacturer	Norton	International Pipe and Ceramics Corp.			Coors Porcelain Corp.	
Grade or Type Designation	A402	TC-352H	GMcB-395	GMcB-352	AD-94	AD-99
% Al_2O_3	99	99	95	99.3	94	99
Specific Gravity	3.80	3.80	3.65-3.70	3.80-3.82	3.59-3.64	3.80-3.90
Modulus of Elasticity (x 10^6 PSI)	53	40	40	50	40	50
Flexural Strength (x 10^3 PSI)		50 min.	35-40	50-55	45-50	47-60
Compressive Strength (x 10^3 PSI)			≈300	≈350	over 300	over 300
Charpy Impact			7.6	7.9	7.6	
Hardness Mohs			9	9		
Rockwell 45N					78	80
Tensile Strength (x 10^3 PSI)					25-27	34-35

Table 2. Physical and Mechanical Properties of Beryllium Plate (data provided by manufacturer)

	Thickness Inches	Heat No.	Plate No.'s Used (1)	U.T.S. PSI x 10^{-3} L	U.T.S. PSI x 10^{-3} T	Y.S. PSI x 10^{-3} L	Y.S. PSI x 10^{-3} T	Elongation % L	Elongation % T	ρ gms/cm^3
Rolled	.2	397-D	H-36-1,2,3,7,8,9,12,13,14,15	71.7	73.6	50.3	50.4	11.1	12.2	1.85
	.2	455-D	H38-1,2,3,4	75.1	75.2	51.8	52.0	13.0	9.6	1.840
	.2	455-D	H41-2,3	70.1	72.0	50.5	50.9	7.9	9.3	1.858
	.2	455-D	H42-1,2,3,4	77.1	71.9	31.3	52.7	19.5	9.0	1.853
	.4	BVR1906	H46-3	68.0	58.0	45.0	45.0	8.4	3.9	1.857
Hot Pressed	.2	662-D	662D-1,2,11	51.6		36.1		2.8		1.848
	.2	2331	-	54.8		37.8		4.2		1.849
	.4	466-E	466E-1,2a,2b,3a,3b,4,7,8,9	51.1		36.1		4.0		1.85
	.4	495	495D-1,3,4,5,6	50.2		36.6		2.2		1.851
	.4	666E	666E-1	47.1		32.0		3.2		1.853

(1) Identification of each plate by number is provided in order that the properties may be associated with the beryllium used for each target in Tables 3, 4, and 10.

Table 3. Ballistic Limit Velocities of Beryllium and Beryllium-Doron Composite Targets Tested with 0.22-inch diameter SKF Grade 1 Spheres

Item No.		Beryllium Plate No.	Thickness inches Be.	Thickness inches Doron	Areal Density lbs/ft^2 Be.	Areal Density lbs/ft^2 Doron	Areal Density lbs/ft^2 Total	Ballistic Limit Velocity, V_L ft/sec
Beryllium Alone								
1	Rolled	H36-13	.205	- - -	1.97	- - -	1.97	1655±50
2	Hot Pressed	662D-2	.206	- - -	1.98	- - -	1.98	1845±60
3	Rolled	H46-3	.403	- - -	3.88	- - -	3.88	3845±85
4	Hot Pressed	466E-7	.407	- - -	3.92	- - -	3.92	3940±40
5	Hot Pressed	566E-1	.406	- - -	3.91	- - -	3.91	3940±90
6	Hot Pressed	495D-1	.407	- - -	3.92	- - -	3.92	3605±65
Beryllium + Doron								
7	Rolled	H41-2	.105	.123	1.01	1.26	2.27(1)	2315±90
			(1/8 x 8 7/8 x 8 7/8)					
8	Rolled	H36-3	.204	.25	1.96	2.51	4.47(3)	4030±50
			(1/4 x 8 7/8 x 8 7/8)					
9	Hot Pressed	662D-1	.207	.25	1.99	2.51	4.50(2)	3770±35
			(1/4 x 8 7/8 x 8 7/8)					
10	Hot Pressed	662D-1	.207	.25	1.99	2.51	4.50(1)	3725±30
			(1/4 x 11 3/4 x 11 3/4)					

(1) The beryllium was placed in contact with the Doron and held in place by pressure sensitive sealing tape.
(2) Beryllium was held to Doron by two "C" clamps.
(3) The beryllium was held to the surface of the Doron by double coated pressure sensitive tape between the Doron and beryllium (Scotch brand No. 406).

Remarks:

Comparison of Items 1 and 2 indicate that the hot pressed plate is superior to the rolled plate although the rolled plate has significantly higher elongation and strength than the hot pressed plate (see Table 2).

For Items 3, 4, 5 and 6 the ballistic limit for the rolled plate is intermediate between the three limits for hot pressed plate. Item 6 of the hot pressed material has lower elongation than Items 4 and 5 (see Table 2). This suggests that for H.P. plate the greater the ductility the higher the ballistic limit.

Comparison of Items 8, 9, 10 indicate that: (a) the higher ductility rolled plate is superior to H.P. plate when used as part of a composite with Doron; (b) size of Doron used, method of support, or method of attaching Be. to Doron did not affect the ballistic limit velocity.

Table 4. Ballistic Limit Velocities of Beryllium and Beryllium-Doron Composite Targets Tested with 22 caliber T-37 Fragment Simulators

Item No.		Beryllium Plate No.	Thickness inches Be.	Thickness inches Doron	Areal Density lbs/ft^2 Be.	Areal Density lbs/ft^2 Doron	Areal Density lbs/ft^2 Total	Ballistic Limit Velocity, V_L ft/sec
Beryllium Alone								
1	Rolled	H36-9	.206	- - -	1.98	- - -	1.98	$V_L < 926$
2	Hot Pressed	662D-11	.400	- - -	3.85	- - -	3.85	$V_L > 2095$
Beryllium + Doron								
3	Rolled	H36-14	.206	.25 (1/4 x 8 x 8)	1.98	2.51	4.49(1)	4300±40
4	Rolled	H36-12,15	.206	.25 (1/4 x 11 x 11)	1.98	2.51	4.49(2)	4310±45
5	Hot Pressed	662D-1	.207	.25 (1/4 x 8 x 8)	1.99	2.51	4.50(2)	3980±30
6	Rolled	H41-3	.105	.123 (1/8 x 8 x 8)	1.01	1.26	2.27(3)	2125±40

(1) Be. held to Doron by two "C" Clamps.
(2) Be. held to Doron by pressure sensitive sealing tape with direct contact between Be. and Doron.
(3) Be. and Doron held together by double coated pressure sensitive tape (Scotch brand No. 406) placed between the Be. and Doron.

Remarks:

Tests of beryllium alone with this missile did not permit determination of missile through-the-target type ballistic limits.

Comparison of Items 3,4 and 5 indicate that: (a) the higher ductility rolled plate is superior to H.P. plate when used as part of a composite with Doron. (see Table 2 for properties); (b) the size of Doron used, method of support, or method of attaching beryllium to Doron did not affect the ballistic limit velocity.

SECRET

Table 5. Protection Ballistic Limit Velocities for Alumina-Doron Targets and Data for other Good Fragment Armor Materials Provided for Purposes of Comparison

Item	Areal Density lbs/ft^2	Protection Ballistic Limit Velocities, V_P, ft/sec: 0.22" Diameter Spheres			22 Caliber Yawed Dart Fragment Simulator			
		Alumina-Doron	Nylon Fabric	Doron	Alumina-Doron	Nylon Fabric	Doron	Titanium 6Al-4V Alloy
1	1.31	910±30	1210	1090	885±20	1500	1260	1070
2	2.16	1495±30	1580	1515	1195±15	1830	1590	1530
3	2.52	1895±25	- - -	- - -	1315±25	1940	1775	1710

Item 1 was purchased from Goodyear Aircraft Company. The alumina was 0.033 inches thick and the Doron backing had an areal density of 0.54 lbs/ft^2.

Items 2 and 3 were obtained from the Chemical Warfare Laboratories and were faced with nominal 0.080 and 0.100-inch thick alumina respectively. The areal density values given were determined at NRL.

Table 6. Tests of Alumina-Doron Targets with Caliber 0.30-inch AP-M2 Projectiles

Item No., Mfr. and % Al_2O_3	Areal Density lbs/ft^2 Alumina	Doron	Total	Doron Size inches	Edges Supported	Protection Ballistic Limit, V_P ft/sec	Trajectory (1) ft
1. Goodyear 95	5.68	3.12	8.80	10 x 10	3	2615±10	2.4
					2	2625±10	6.5
					In frames (2)	2640 (3)	10.75
2. Goodyear 99	6.01	3.09	9.10	10 x 10	3	2865±15	2.4
					2	2891 (4)	6.5
					In frames	2934 (5)	6.5
3. NRL 95	5.70	2.90	8.60	8 7/8 x 8 7/8	2	<2685 (6)	6.5
4. NRL 95	4.95	2.93	7.88	10 x 10	2	2340±25 (7)	6.5

(1) Distance from muzzle of gun barrel to target.
(2) Targets were held between two one-half inch thick pieces of aluminum alloy 12 x 12 inches with a central cut out area of 7 1/8 x 7 1/8 inches. The two pieces of aluminum were held together with the Doron between them by eight 1/4 inch screws. This assembly was held to 1 x 1 inch steel posts by "C" clamps.
(3) At this velocity three fragments passed through the target and dented the witness plate but did not puncture it so that light could pass through. This was taken to be very close to the protection limit velocity.
(4) At 2891 ft/sec there were two small holes in the witness plate, thus this confirms the protection limit of 2865 ft/sec.
(5) At 2934 ft/sec under these test conditions, a 1-1/2 inch diameter hole was in the witness plate. This shows that if clamping in frames results in an increase in the protection limit that it is a small effect (less than 85 ft/sec).
(6) The targets for Item 3 were made from alumina removed from Item 1 and bonded to NRL procured Doron using Proseal 890 resin. At 2685 ft/sec the AP-M2 projectile penetrated the target and made a 1-1/4 inch diameter hole in the witness plate. This indicates that there is no substantial difference between this target and Item 1.
(7) The targets for Item 4 were made from NRL procured alumina (GMcB-395) and Doron taken from Goodyear targets. A few layers of fiberglass fabric were stripped from the Doron to obtain clean and undamaged surfaces. The alumina and Doron were bonded with Proseal 890. This data point is included on Fig. 10. It is clear that the performance in tests with AP-M2 projectiles is not different from other items made from the NRL procured alumina and NRL procured Doron.

SECRET

Table 7. Effect of Bonding Agent Used Between Doron and Alumina

Item No., Mfr. and % Al_2O_3	Areal Density lbs/ft^2 Alumina	Doron	Total	Doron Size inches	Edges Supported	Trajectory ft	Bonding	Protection Ballistic Limit Velocity, V_P ft/sec AP-M2	Ball M-2
1. NRL 95	4.93	2.51	7.44	8 7/8 x 8 7/8	2	6.5	Proseal 890	2190±25	
					In frames	6.5	" "	2275±25	
					In frames	10.75	" "	2200±40	
2. NRL 99	5.07	2.51	7.58	8 7/8 x 8 7/8	2	6.5	Proseal 890	2205±30	
					In frames	6.5	" "	2210±45	
					4	10.75	" "		2700±40
3. NRL 95	4.93	2.51	7.44	8 7/8 x 8 7/8	2	6.5	Epoxy Resin	2165±5	
					4	10.75	" "		2715±40
4. NRL 99	5.11	2.51	7.62	8 7/8 x 8 7/8	4	10.75	Double Surface pressure sensitive tape.	2275±25	

Table 8. Tests of Alumina-Doron with Caliber 0.30-inch Ball-M2 Projectiles

Item No., Mfr. and % Al_2O_3	Areal Density lbs/ft^2 Alumina	Doron	Total	Doron Size inches	Edges Supported	Trajectory (1) ft	Protection Ballistic Limit Velocity, V_P ft/sec
1. Goodyear 95	5.68	3.12	8.80	10 x 10	3	2.4	3040±80
					2	6.5	3095±20
					In frames (2)	10.75	3075±25
2. NRL 99	5.07	2.51	7.58	8 7/8 x 8 7/8	4	10.75	2700±40
3. NRL 99	5.11	2.65	7.76	12 x 12	4	10.75	2865±35
4. NRL 99	5.15	3.65	8.80	12 x 12	4	10.75	3155±45
5. NRL 95	5.70	2.90	8.60	8 7/8 x 8 7/8	2	6.5	>2967 (3)
6. NRL 95	4.93	2.51	7.44	8 7/8 x 8 7/8	4	10.75	2715±40
7. NRL 99	4.10	2.05	6.15	12 x 12	4	10.75	1990±45

All targets except Item 4, 6, and 7 above were bonded with Proseal 890 resin applied as described in the body of this report. The alumina and Doron for Item 4 and 7 were held together by double coated pressure sensitive tape (Scotch Brand No. 406). The alumina and Doron for Item 6 were bonded with an epoxy resin.

(1) Distance from muzzle of gun barrel to target.

(2) Targets were held between two one-half inch thick pieces of aluminum alloy 12 x 12 inches with a central cut out area of 7 1/8 x 7 1/8 inches. The two pieces of aluminum were held together with the Doron between them by eight 1/4 inch screws. This assembly was held to 1 x 1 inch steel posts by "C" clamps.

(3) The target for Item 5 was made from alumina removed from Item 1 and bonded to NRL procured Doron with Proseal 890. Complete penetration of the target did not occur at 2967 ft/sec. It was estimated that the V_P would be at least 100 ft/sec higher.

The results of tests on Item 1 show that for the 10 x 10 inch Doron backing, where relatively little delamination occurred for any of the mounting methods, the means of support has little if any effect.

Table 9. Tests with Caliber 0.30-inch AP-M2 Projectiles

Item No., Mfr. and % Al_2O_3	Areal Density lbs/ft^2 Alumina	Doron	Total	Doron Size inches	Edges Supported	Trajectory ft	Protection Ballistic Limit Velocity, V_P ft/sec
1. NRL 95	3.95	2.28	6.23	8 7/8 x 8 7/8	2	6.5	1555±80
2. NRL 95	6.83	3.02	9.85	12 x 12	4	10.75	3135±25
3. NRL 99	5 11	2.65	7.76	12 x 12	4	10.75	2308 (1)
4. NRL 99	5.15	3.65	8.80	12 x 12	4	10.75	2615±35
5. NRL 99	5.11	1.56	6.67	12 x 12	4	10.75	1775±15

Items 1 and 3 were bonded with Proseal 890 as described in the body of this report.

Items 2, 4, and 5 were held together with double coated pressure sensitive tape (Scotch Brand No. 406).

(1) One shot penetrated target, - 1 1/2 inch diameter hole in witness plate (For comparable targets, except for area of Doron, see Table 7).

Table 10. Tests of Three-Phase Composites

Item No., Mfr. and % Al_2O_3	Be. Plate Nos. Used	Areal Density lbs/ft^2 Alumina	Be.	Doron	Total	Test Missile Caliber 0.30-inch	Protection Ballistic Limit Velocity, V_P ft/sec
1. NRL	H38-1,2,3,4	- - -	2.04	3.08	9.04	AP-M2	2320±85
	466E-3,3*,4,8	- - -	+3.92				
2. NRL 99	H42-1,2,3,4	2.16	2.05	1.98	6.19	Ball-M2	2235∓10
3. NRL 99	H36-1,2,7,8	2.02	2.02	2.02	6.06	AP-M2	1650±50
4. NRL 99	466E-1,2,2*,5,6	3.95	3.92	1.56	9.43	AP-M2	3080±10

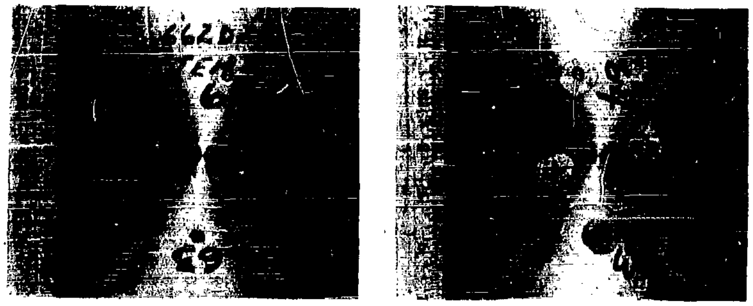
*Two plates supplied with the same identification number.

Table 11. Selected Properties of Some Hard Materials

Material	Knoop Hardness KHN_{100}	Density gms/cc	Young's Modulus PSI x 10^{-6}
Diamond	8000 - 8500	3.5	155
Boron Carbides	2670 - 2950	2.5	66
Silicon Carbides	2130 - 2760	3.2	77
Titanium Carbide	2350 - 2620	4.25	46
Aluminum Oxide	1860 - 2200	4.0	76
Tungsten Carbide	1570 - 2140	15.2 - 14.7	105
Tool Steel, R_c 60.5	730 - 760	7.8	30

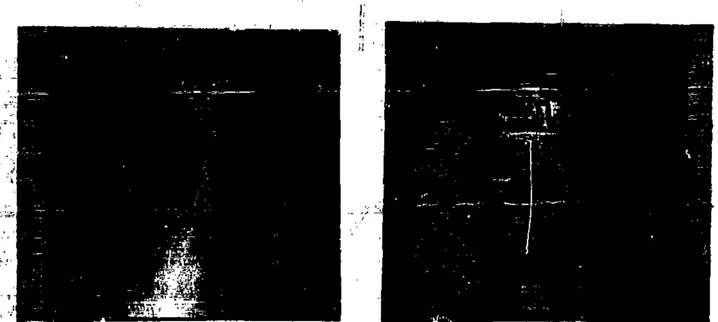
Properties abstracted from published reference sources.

This table was not intended to provide a comprehensive list of potential materials for use as facing components of composite targets. Other compounds of the major elements listed may be equally attractive, for example, titanium boride or titanium nitride. The tool steel, diamond and tungsten carbide were included to provide a frame of reference with respect to hardness for materials with which the reader may be familiar.



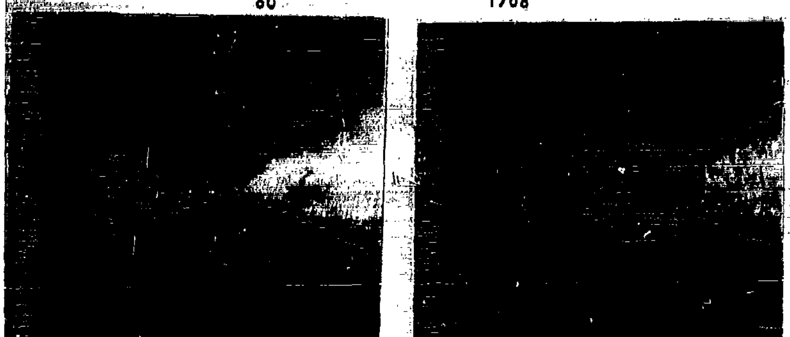
Hot Pressed Plate
7/32-Inch Steel Sphere Projectile

Shot No.	Velocity ft/sec
61	1740
62	1663
63	1903
64	1790



Rolled Plate
7/32-Inch Steel Sphere Projectile

Shot No.	Velocity ft/sec
56	1889
57	1451
58	1761
59	1605
60	1706



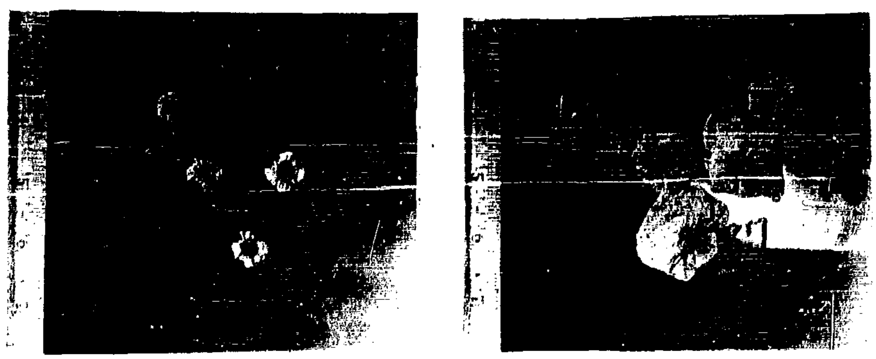
Rolled Plate
Caliber 0.22-Inch T-37 Fragment Simulator

Shot No.	Velocity ft/sec
91	926

Fig. 1 - Typical results of impacts on 0.20-inch thick beryllium targets with steel spheres and T-37 fragment simulators

Hot Pressed Plate

Shot No.	Velocity ft/sec
65	2478
66	2600
67	2904
68	3020
69	3250
70	3415
71	3539
72	3670



Rolled Plate

Shot No.	Velocity ft/sec
86	4225
87	3945
88	3929
89	3929
90	3760

Fig. 2 - Typical results of impacts on 0.40-inch thick beryllium targets with 7/32-inch steel sphere projectiles

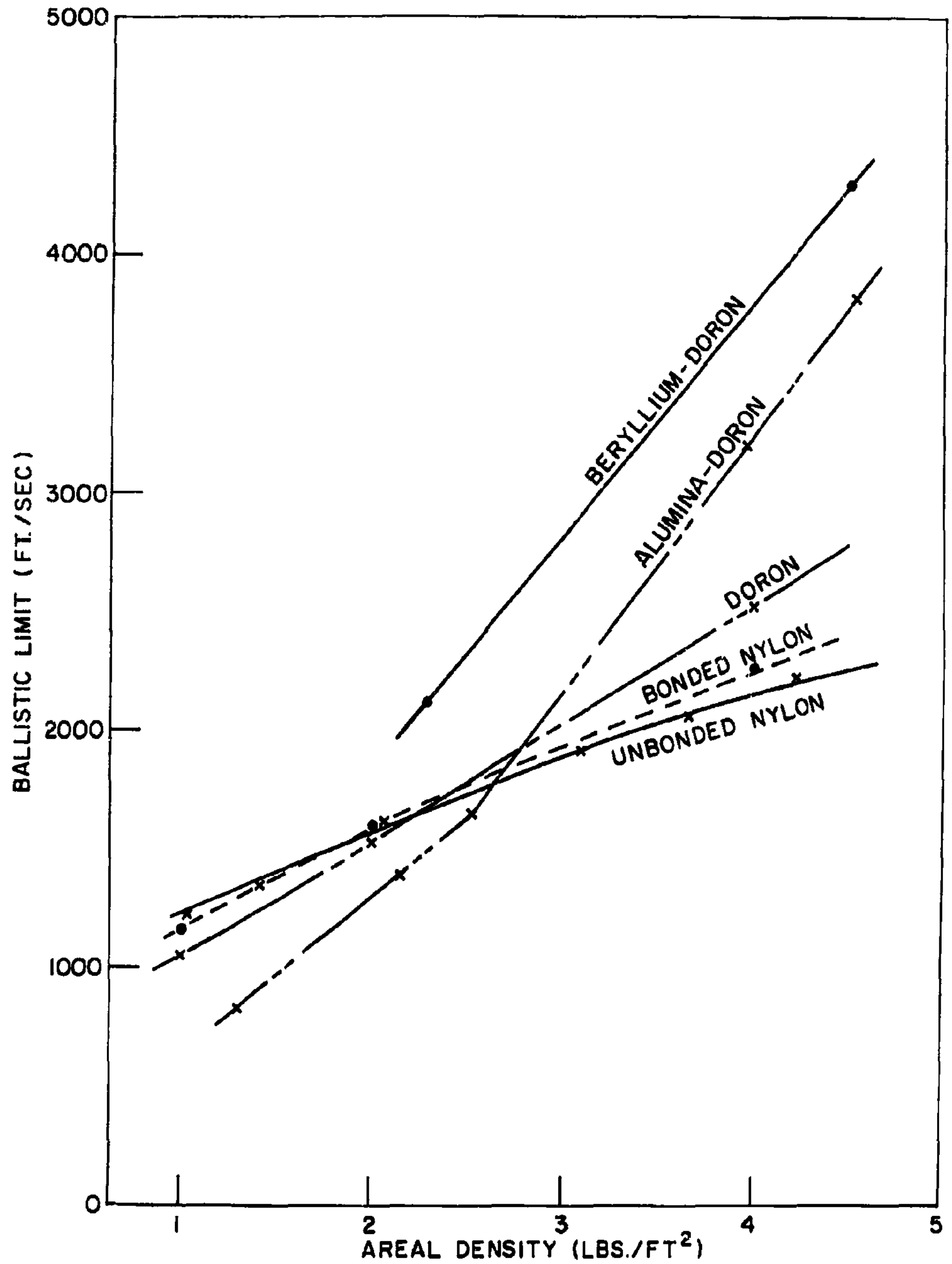


Fig. 3 - Comparison of beryllium-Doron and alumina-Doron composites with other fragment armor materials against T-37 fragment simulator

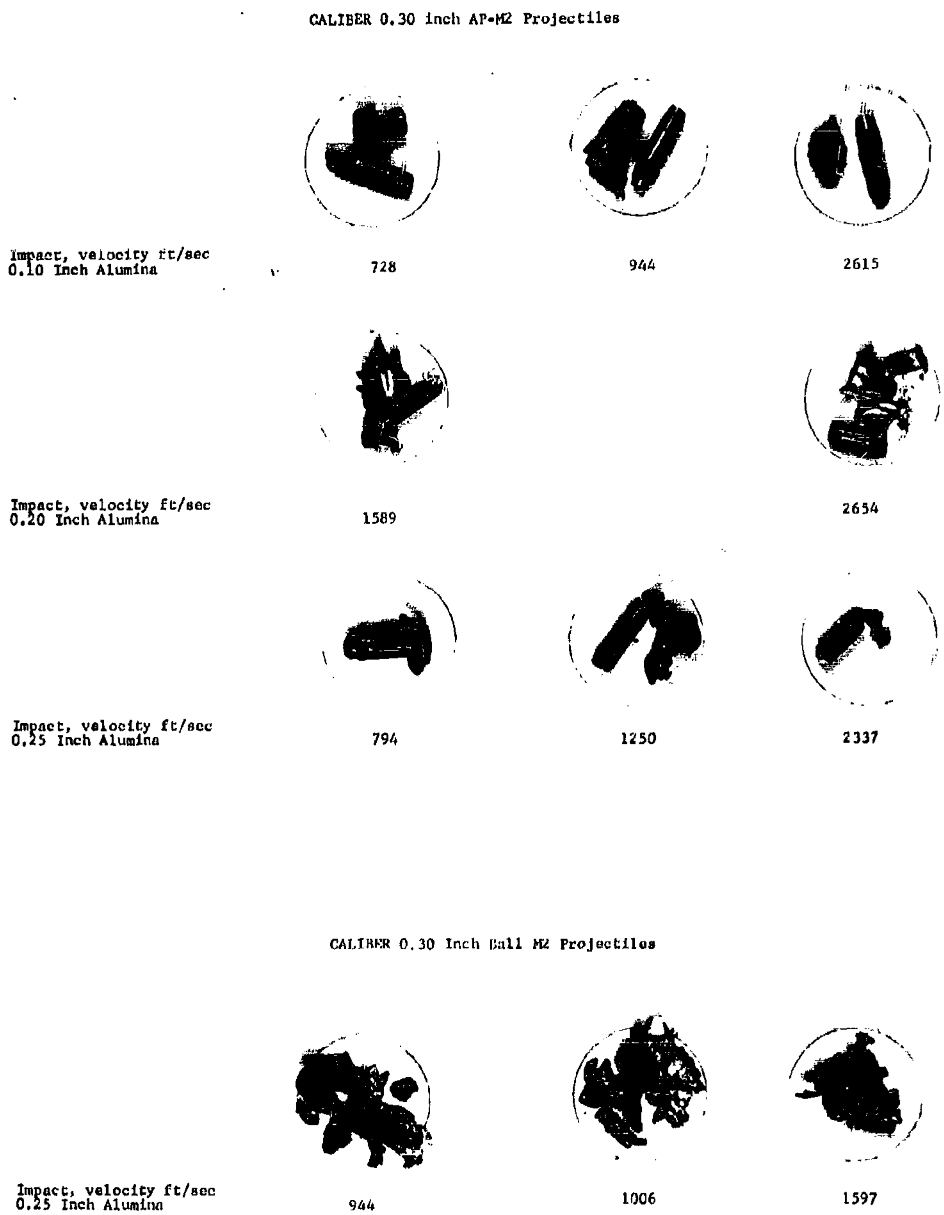


Fig. 4 - Blunting, deformation, and break-up of projectiles at various velocities (all backed with 0.37 inch Doron)

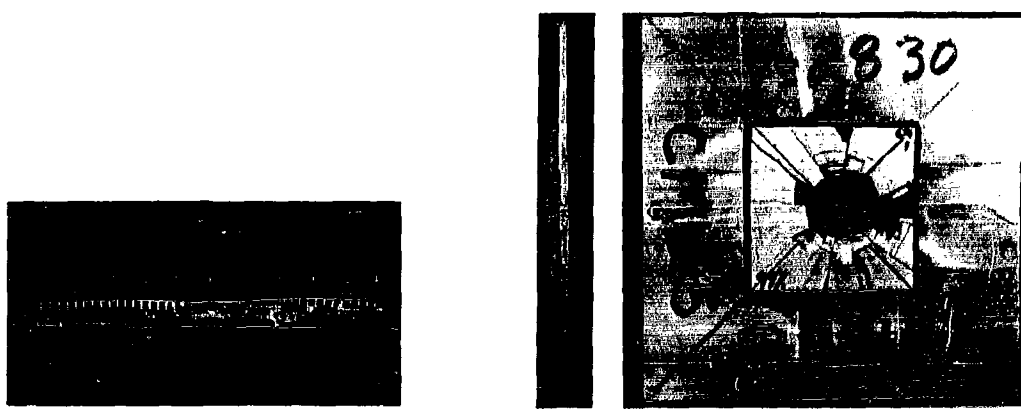
2856	Impact velocity-ft/sec	2237
10 × 10	Doron: Size (in.)	8-7/8 × 8-7/8
~0.30	thickness (in.)	~0.25
5-1/2 × 5-1/2	Alumina: Size (in.)	5 × 5
≈0.30	thickness (in.)	0.258
3 Edges	Target support	2 Edges

Impact velocity-ft/sec	2308
Doron: Size (in.)	12 × 12
thickness (in.)	0.25
Alumina: Size (in.)	5 × 5
thickness (in.)	0.258

Target support – 4 Edges

Fig. 5 - Typical targets impacted with caliber 0.30 in. APM2 projectiles

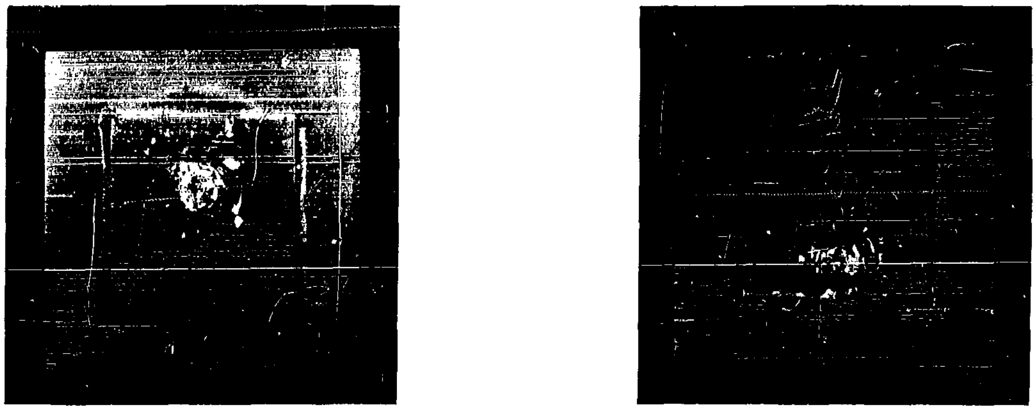
2961	Impact velocity-ft/sec	2655
10 × 10	Doron: Size (in.)	8-7/8 × 8-7/8
0.301	thickness (in.)	0.25
5-3/4 × 5-3/4	Alumina: Size (in.)	5 × 5
≈0.3	thickness (in.)	.256
3 Edges	Target support	4 Edges



Reverse buckling

3006	Impact velocity-ft/sec	2830
10 × 10	Doron: Size (in.)	12 × 12
≈0.30	thickness (in.)	0.25
5 × 5	Alumina: Size (in.)	5 × 5
≈0.30	thickness (in.)	0.258
In Frame	Target support	4 Edges

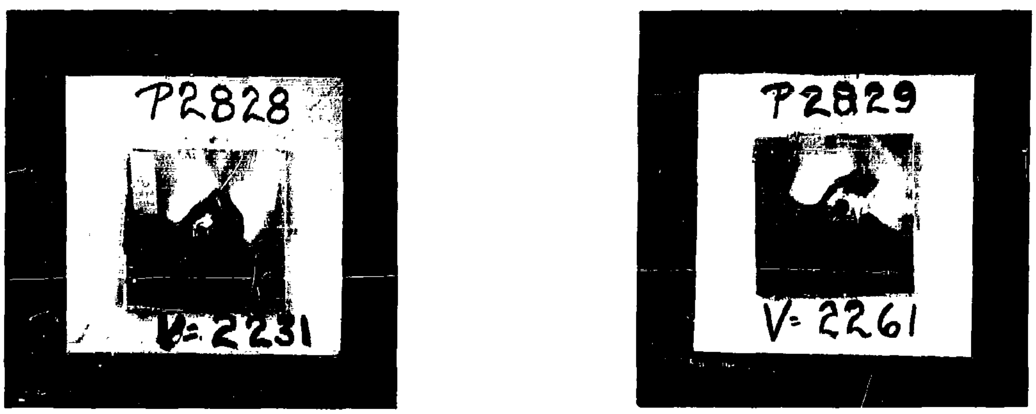
Fig. 6 - Typical targets impacted with caliber 0.30 in. ball M-2 projectiles



2619 ft/sec Incomplete penetration | Impact velocity | 2548 ft/sec Incomplete penetration

Center impacts V_P = 2615 ft/sec

Fig. 7 - Off-center impacts with caliber 0.30 in. AP-M2 projectile. Targets same as item 1, Table 3.



2231 ft/sec Incomplete penetration | Impact velocity | 2261 ft/sec Incomplete penetration

Targets without aluminum facing – V_P = 2275 ft/sec

Fig. 8 - Caliber 0.30 in. AP-M2 impact on targets with 0.030 in. 2024-T3 aluminum facing.

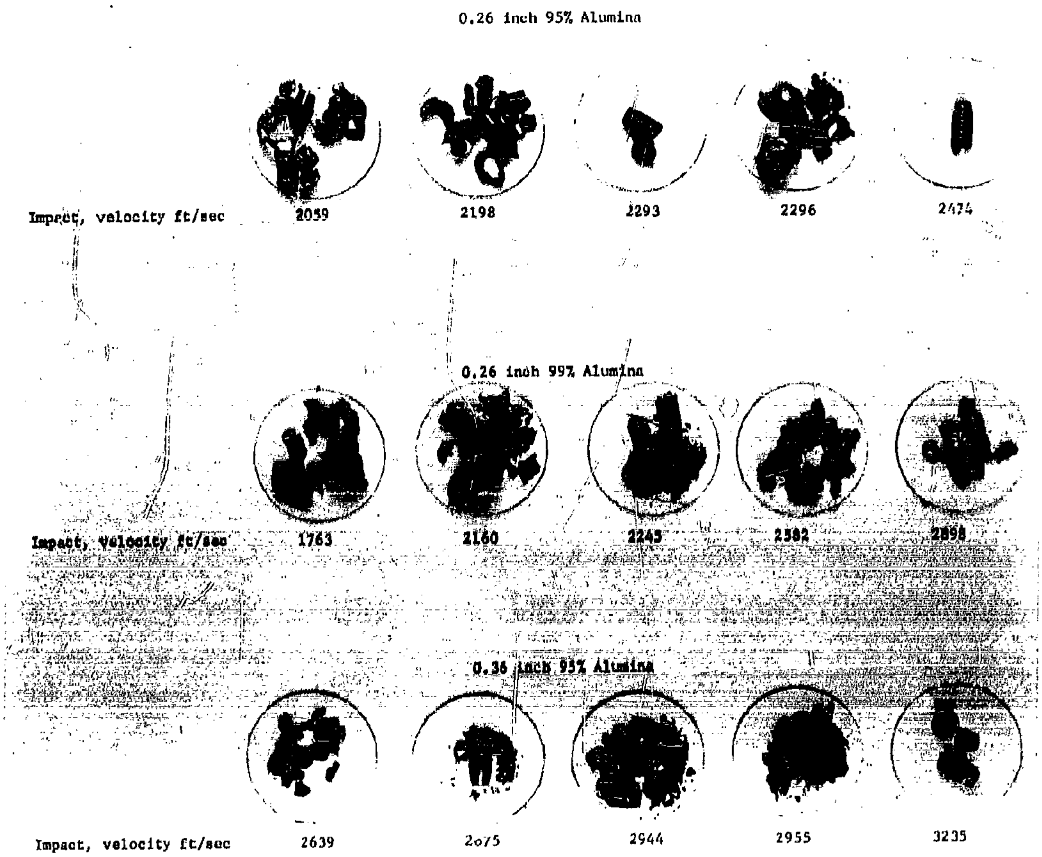


Fig. 9 - Typical examples of AP-M2 projectile breakup.

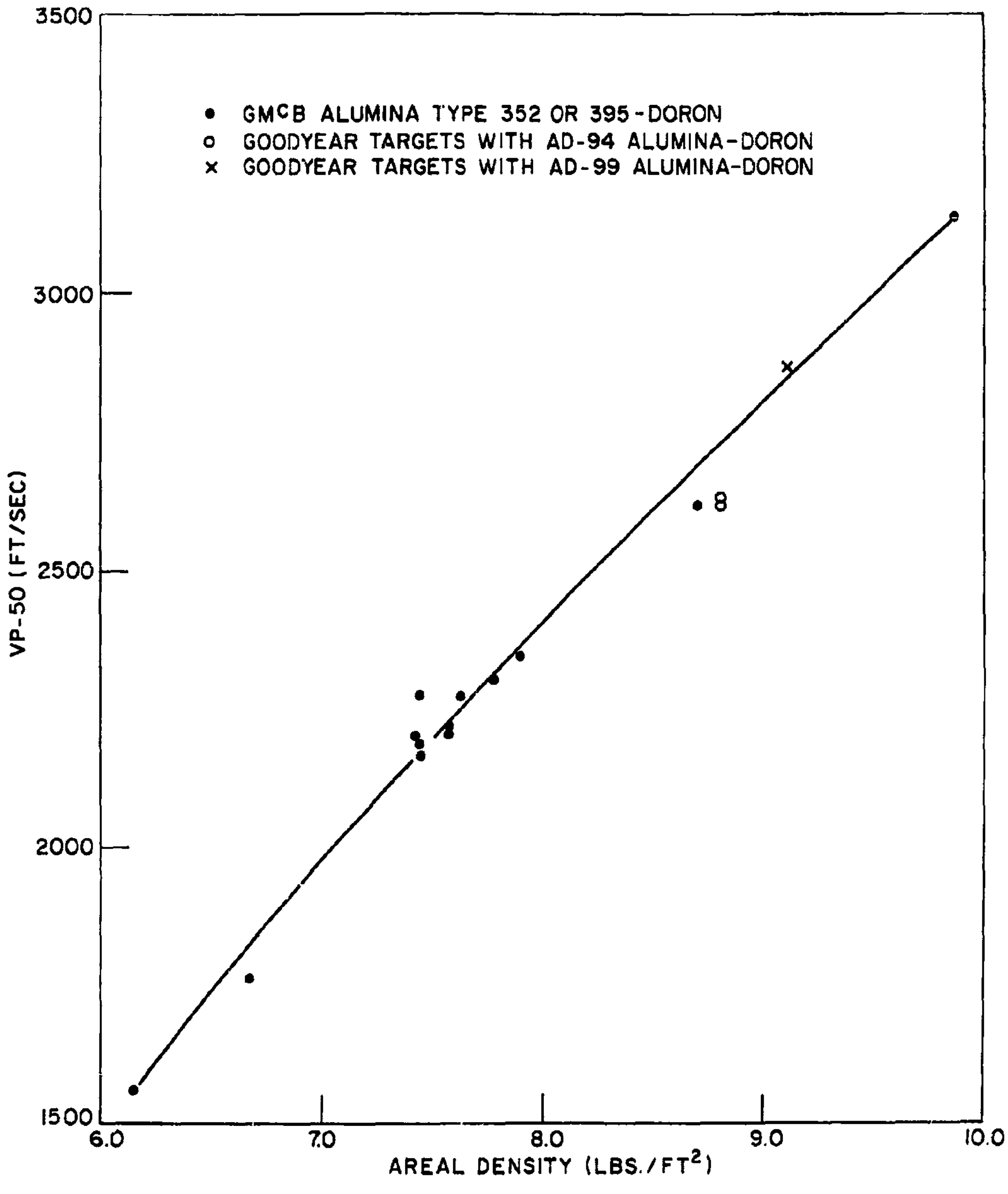


Fig. 10 - Protection ballistic limit velocity against caliber 0.30-inch AP-M2 projectile for alumina-Doron composite

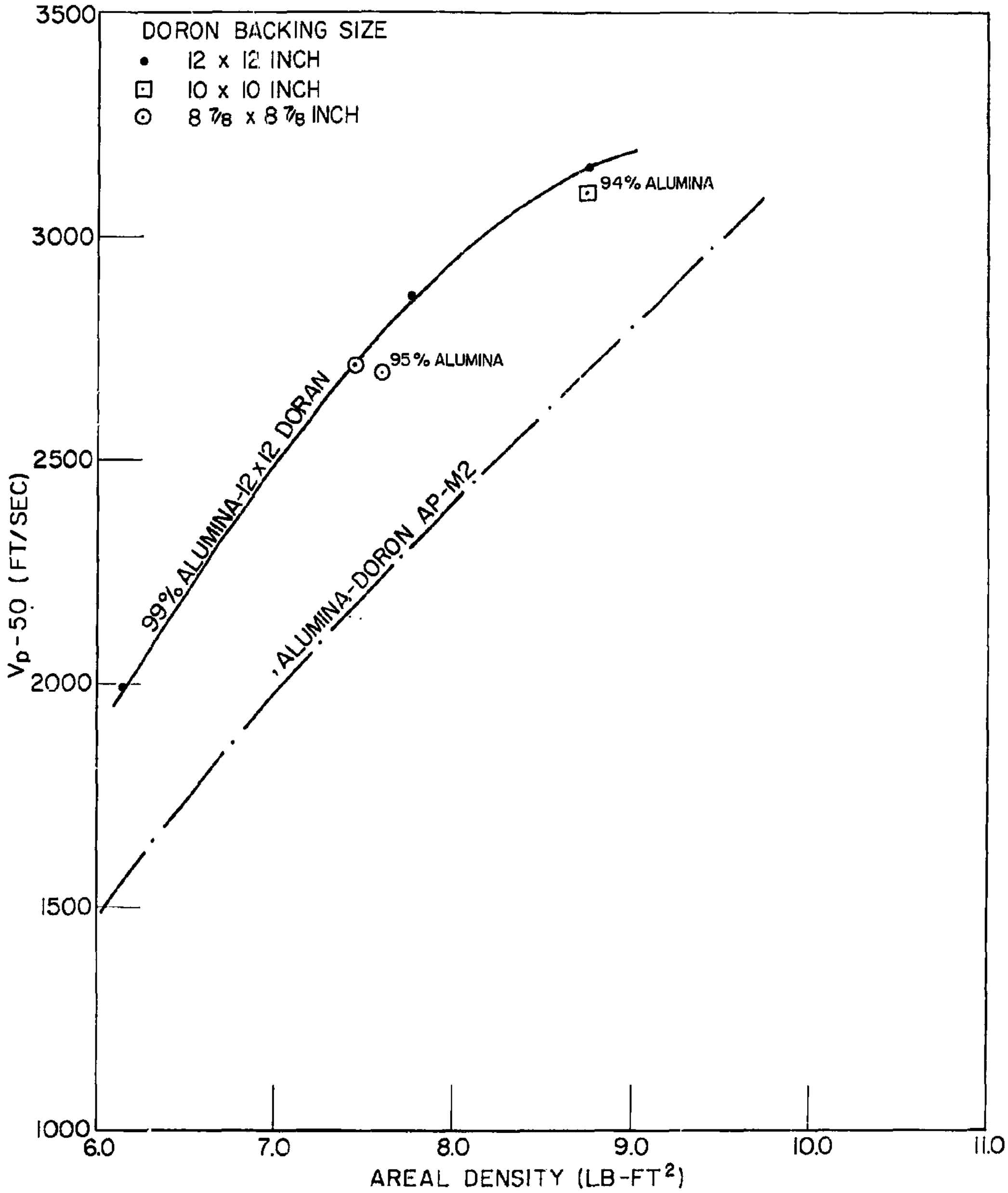


Fig. 11 - Protection ballistic limit velocity against caliber 0.30-inch Ball-M2 projectile for alumina-Doron composites

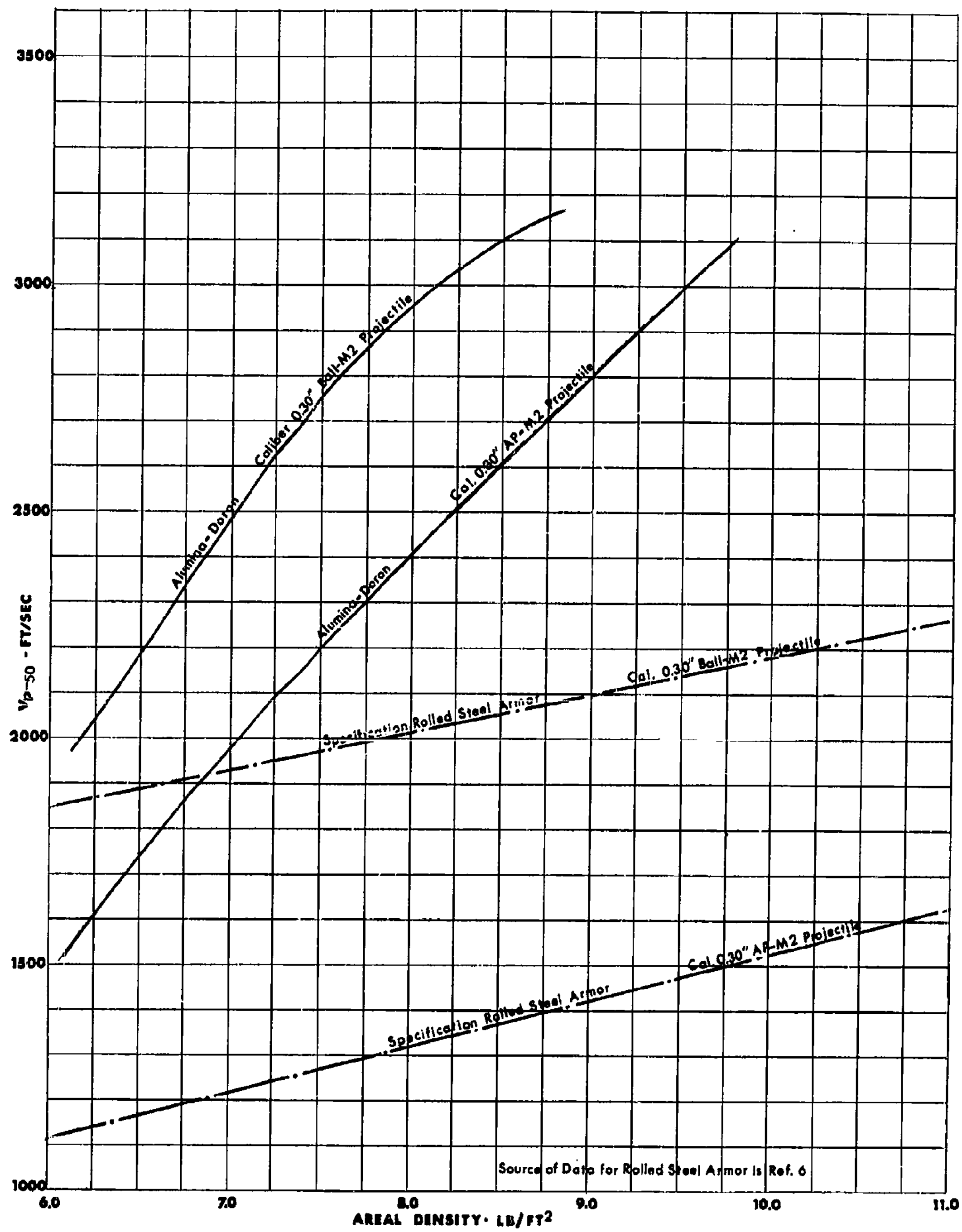


Fig. 12 - Comparison of alumina-Doron composite target with specification rolled steel armor against caliber 0.30-inch projectiles

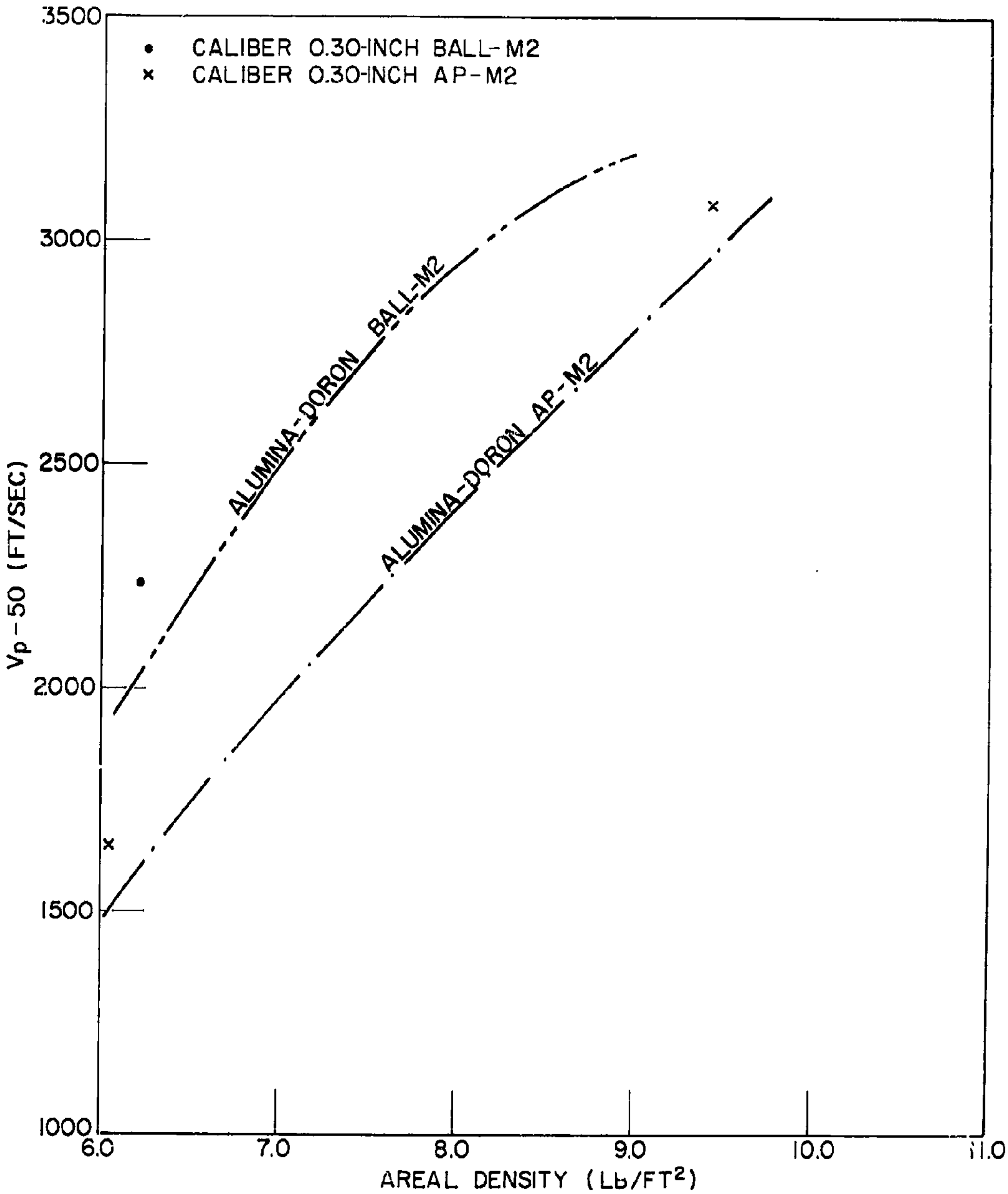
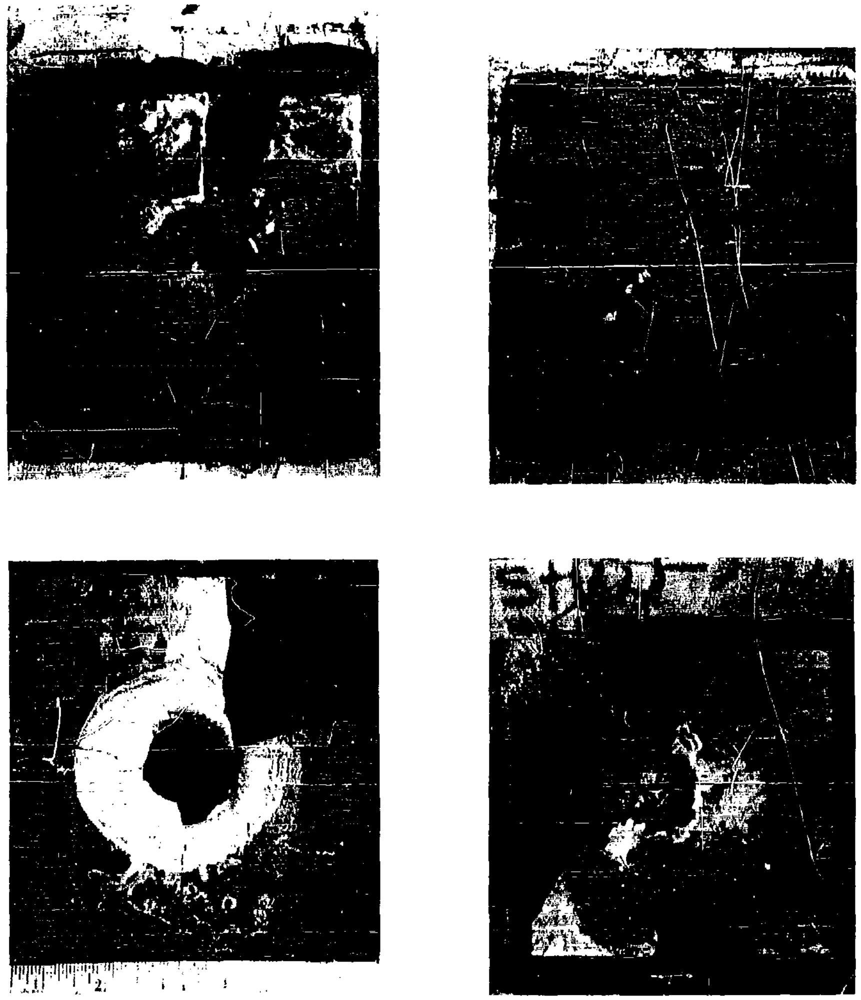


Fig. 13 - Protection ballistic limit velocity against caliber 0.30-inch projectiles for alumina-beryllium-Doron composite



Upper Left - After impact at 2670 ft/sec, shows two segments of alumina in upper half and the beryllium which appears to be broken into four major pieces

Upper Right - Same target with approx. 0.8 of the beryllium removed to show beryllium spall still adhering to the Doron

Lower Left - Same target showing beryllium surface which was bonded to Doron at time of impact

Lower Right - After impact at 2922 ft/sec

Fig. 14 - Typical appearance of a tri-phase composite impacted with caliber 0.30-inch AP-M2 projectiles

DISTRIBUTION

	Copy No.
Office of the Director of Defense (R and E) Attn: Dr. Earl T. Hayes, Asst. Director (Materials)	1
Dir., Advanced Research Projects Agency, Washington, D.C. Attn: CDR Mavis X. Polk Mr. P. J. Franklin	2 3
Defense Documentation Center (DDC), Arlington, Va. (20)	4-23
CG, U. W. Army Materiel Command, Washington, D. C. Attn: AMCRD-RC-M, L. S. Croan	24
CG, Natick Laboratories, Natick, Mass. 01762 Attn: Dr. George Thomas	25
CG, U. S. Continental Army Command, Fort Monroe, Va. Attn: Aviation Section	26
CG, U. S. Army Tank-Automotive Center, Warren, Mich. 43090 Attn: H. Spiro	27
CO, Aberdeen Proving Ground, Aberdeen Proving Ground, Md. Attn: STEAP-DS-TU, W. Pless	28
CO, Frankford Arsenal, Philadelphia, Pa., 19137 Attn: SMUFA-1320, H. Markus	29
CO, Limited War Laboratories, Aberdeen Proving Ground, Md. Attn: J. L. Baer	30
CO, Picatinny Arsenal, Dover, New Jersey 07801 Attn: W. J. Powers	31
CO, U. S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Md. 21005 Attn: AMXBR, H. Kostiak	32
CO, U. S. Army Materials Research Agency, Watertown, Mass. 02172 Attn: P. V. Riffin	33

DISTRIBUTION (Cont'd)

	Co[illegible] No.
CO, U. S. Army Chemical Research and Development Laboratories, Edgewood Arsenal, Maryland 21010 Attn: Mr. George Stewart	[illegible]4
CO, U. S. Army Transportation Research Command, Fort Eustis, Virginia Attn: F. P. McCourt	[illegible]5
Commander, NOL, Silver Spring, Maryland	[illegible]6
Commanding Officer, NWL, Dahlgren, Virginia	[illegible]7
BuWeps Attn: Code RRMA-2, Mr. T. Kearns (3) RAAV-541	 38-[illegible]0 [illegible]
CO, U. S. Naval Medical Field Research Laboratory Camp Lejeune, North Carolina Attn: Technical Library	[illegible]2
NASA, 600 Independence Ave., Washington, D. C. Attn: Technical Library	[illegible]3
CDR, Air Force Systems Command, Andrews AFB, Washington, D. C. Attn: Technical Library	[illegible]4
Commandant, U. S. Marine Corps, Washington, D. C. Attn: A04D AX	 [illegible]5 [illegible]6
Commandant, MCLFDC, Marine Corps Schools, Quantico, Va. Attn: Ground Combat Section	[illegible]7
CDR, Air Force Materials Lab., Wright-Patterson Air Force Base, Ohio Attn: Code MAMP	[illegible]8
ONR Attn: Code 463	[illegible]9
NRL, Code 6214 6210 4005 1073	50-[illegible]1 [illegible]2 [illegible]3 [illegible]4
DDC, Alexandria, Va. Attn: TIPDR	55-[illegible]5

CONFIDENTIAL

Naval Research Laboratory
Technical Library
Research Reports Section

DATE: November 21, 2002

FROM: Mary Templeman, Code 5227

TO: **Code 6300 Dr Gubser**

CC: Tina Smallwood, Code 1221.1 ts/11/6/03

SUBJ: Review of NRL Reports

Dear Sir/Madam:

Please review NRL Memo Reports 1760, 1541 and 1927 for:

- ☑ Possible Distribution Statement
- ☑ Possible Change in Classification

Thank you,

Mary Templeman

Mary Templeman
(202)767-3425
maryt@library.nrl.navy.mil

The subject report can be:

- ☒ Changed to Distribution A (Unlimited)
- ☒ Changed to Classification unclassified
- ☐ Other:

D U Gubser 1/2/03

Signature Date

-- 1 OF 1
-- 1 - AD NUMBER: 351091
-- 2 - FIELDS AND GROUPS: 11/4, 19/10
-- 3 - ENTRY CLASSIFICATION: UNCLASSIFIED
-- 5 - CORPORATE AUTHOR: NAVAL RESEARCH LAB WASHINGTON D C
-- 6 - UNCLASSIFIED TITLE: BALLISTIC EVALUATIONS OF COMPOSITE ARMOR
-- 8 - TITLE CLASSIFICATION: UNCLASSIFIED
--10 - PERSONAL AUTHORS: FERGUSON,W. J. ;SEIBERT,E. R. ;SKOWRONEK,C. J. ;
--11 - REPORT DATE: JUN 1964
--12 - PAGINATION: 48P MEDIA COST: $ 7.00 PRICE CODE: AA
--14 - REPORT NUMBER: NRL-MR-1541
--20 - REPORT CLASSIFICATION: CONFIDENTIAL
--22 - LIMITATIONS (ALPHA): NOTICE: ALL RELEASE OF THIS DOCUMENT IS
-- CON-TROLLED. ALL CERTIFIED REQUESTERS SHALL OBTAINRELEASE APPROVAL
-- FROM NAVAL RESEARCH LAB.,WASH. 25, D. C.
--23 - DESCRIPTORS: (*ARMOR, PERFORMANCE (ENGINEERING)), ARMOR-
-- PIERCING AMMUNITION, TERMINAL BALLISTICS, PENETRATION, FIRING TESTS
-- (ORDNANCE), STRESSES, LOADING (MECHANICS)
--24 - DESCRIPTOR CLASSIFICATION: UNCLASSIFIED
--29 - INITIAL INVENTORY: 20
--32 - REGRADE CATEGORY: C
--33 - LIMITATION CODES: 5
--35 - SOURCE CODE: 251950

--36 - ITEM LOCATION: DTIC
--38 - DECLASSIFICATION DATE: OADR
--40 - GEOPOLITICAL CODE: 1100
--41 - TYPE CODE: N
--43 - IAC DOCUMENT TYPE: